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1 Technical Field

Lightweight Radar ESM systems where multiple antennas are used to determine direction of arrival, and emitter characterization of radar pulses.

2 Technical Background

2.1 The Problem Area

The receiver needs to cover a wide radar frequency band (typ 2-18 GHz) with 360° of angular coverage. At the same time, the system must perform thorough analysis of each received pulse in order to identify radar emitters. The system should be man-portable in field, and should be able to operate with battery power. Multiple systems should be able to find emitter position (both bearing and range).

2.2 Known solutions

Three main solutions are known:

1. <u>Wide bandwidth crystal receiver</u>
   A crystal receiver may be used to cover the entire bandwidth. This receiver detects the signal envelope, and coarse pulse parameters may be measured. At least 4 such receivers are needed to achieve and angular coverage of 360°.

2. <u>Parallel receivers</u>
   Multiple receivers are used to cover the entire bandwidth. With current technology, approximately 20 parallel receivers may be used to divide the entire bandwidth into sub-GHz channels, which in turn may be processed with current digital processors. In order to cover 360°, at least 4 such receiver packs with the antennas pointing in different directions are needed to perform direction finding.

3. <u>Scanning receivers</u>
   In order to perform detailed pulse analysis, a single narrowband receiver may be used for each antenna direction. The receiver is used to scan the entire frequency bandwidth sequentially. Detailed pulse analysis may be performed within the narrow instantaneous bandwidth.

2.3 Problems with known solutions

The wide bandwidth crystal receiver is capable to perform coarse pulse analysis only. Important pulse parameters such as carrier frequency and frequency or phase modulation are lost. Thus emitter characterization is coarse at best. In a scenario with multiple emitters, the use of two or more ESM-receivers at different locations to position the target emitter may fail since emitters received in one receiver may be associated with a different emitter received in other receivers.

The parallel receiver solution performs high quality pulse measurement, and may therefore be used for emitter characterization. Determining emitter position may be performed when two or more receivers at different locations are used, since each pulse and each emitter may be identified. On the other hand, this solution requires massive parallelism in both radio hardware and processing hardware. The result is high weight and very high power consumption rendering this concept useless for man-portable operation.

The scanning receiver may be built as a compact unit with low power consumption, and may also provide detailed pulse measurement. The problem with this receiver configuration is the low probability of intercept due to low instantaneous bandwidth. Radars operating with single scan policy will most probably not be detected.

3 The Invention

3.1 Description

The ESM receiver system consists of two units, namely: (1) The Receiver unit (Antenna, Receiver and Navigation sub-unit) and (2) The Processing Unit as shown in figure 1 below.

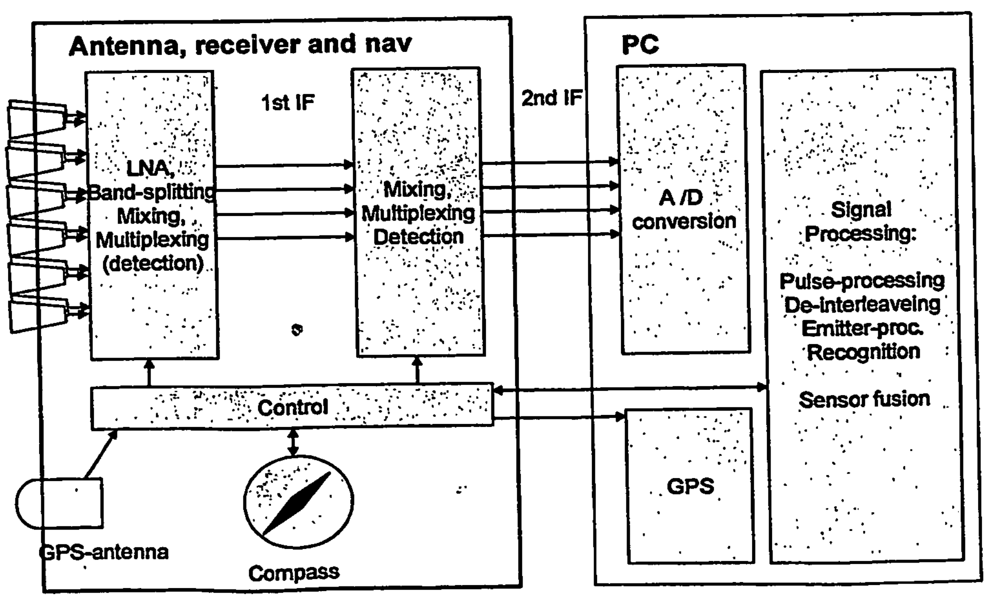

Figure 3-1: System overview

3.1.1 The Receiver Unit

12 antenna elements are used to cover 2 to 18 Ghz in 6 directions. The first stage in the receiver split the total band into four bands with an IF bandwidth of 4 GHz. The four bands are multiplexed into a single IF channel for each of the antenna sets (based on masks set from the processing unit). IF channels of opposing antennas are multiplexed into one channel, thus providing a total of three 1st IF channels.

In order to determine direction and frequency of incoming pulses, broadband pulse detection is performed in each of the original channels before multiplexing. (See Figure 3-5)

The second stage multiplexes the 4 GHz IF into narrowband 2nd IF channels of 1 GHz which are sent to the processing unit for digitalization and processing. Figure 3-2 shows how the frequency band is subdivided into sub-bands and down-converted.

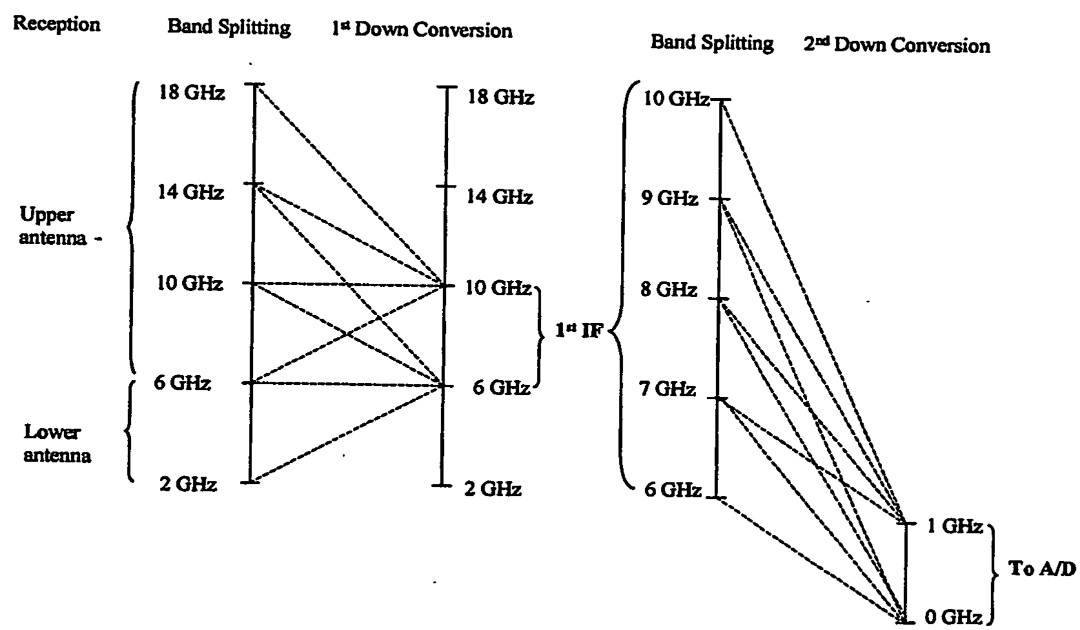

Figure 3-2: Frequency band splitting and down conversion

In addition to the antenna/receiver chain, this unit contain an attitude determination unit (compass) and a GPS antenna. All is contained within a single unit that may be mounted either on a tripod or fixed on an antenna mast. Figure 3-1 shows a model of the receiver.

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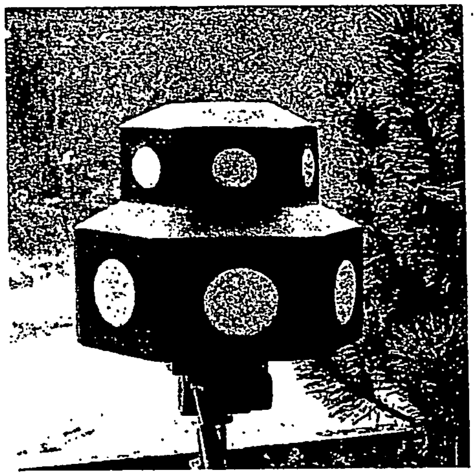


Figure 3-3: Receiver Physical Design

3.1.2 The Processing Unit

A four-channel 1GS/s A/D converter is used for digitalisation of the receiver channels. A GPS receiver is used for position determination, and the compass in the Antenna unit is read for antenna attitude determination. The processing unit digitises pulses received, performs pulse-processing, de-interleaving and multi-path analysis before emitter processing is performed. The following process is performed on the detected pulses:

- For each pulse:
    - o Convert pulse series to complex form
    - o Measure Pulse peak amplitude and average amplitude
    - o Measure Direction of Arrival (DOA) based on amplitude difference and phase difference in the three channels
    - o Measure Pulse Width (the duration of the pulse)
    - o Measure Carrier frequency (corrected according to sub-band detectors)
    - o Measure Time of Arrival (TOA)
    - o Insert pulses into frequency / DOA histogram

- After detection of a predetermined number of pulses or upon reaching a predetermined time limit perform:
    - o De-interleaving (identifying which pulses comes from the same emitter):
        - Based on frequency/ DOA histogram
    - o Perform emitter analysis:
        - Improve DOA measurement by averaging
        - Perform echo-recognition by identifying "same" emitter in different directions
        - Perform emitter antenna analysis (rotation speed and beam width) based on pulse amplitudes
    - o Perform emitter classification based on all emitter parameters (excluding DOA)

  - Perform emitter recognition based on all emitter parameters (excluding DOA) and sampled pulse waveform compared to emitter library.
- If multiple ESM-sensors observes the same area, DOA information from neighbouring ESM-sensors to triangulate in order to find emitter position

For details on the algorithms see section 3.1.4.

At this stage, data may be displayed locally or set to the network for sensor fusion with other sensors. If multiple ESM sensors are connected in a network, local sensor fusion may be performed to provide target positioning. In addition emitter recognition analysis is performed using either a local or network based emitter database. Figure 3-4 shows the use of multiple ESM-receivers for emitter position determination. A common emitter database (shown as a green oval on shore) is used to convey emitter information from one ESM-receiver to another.

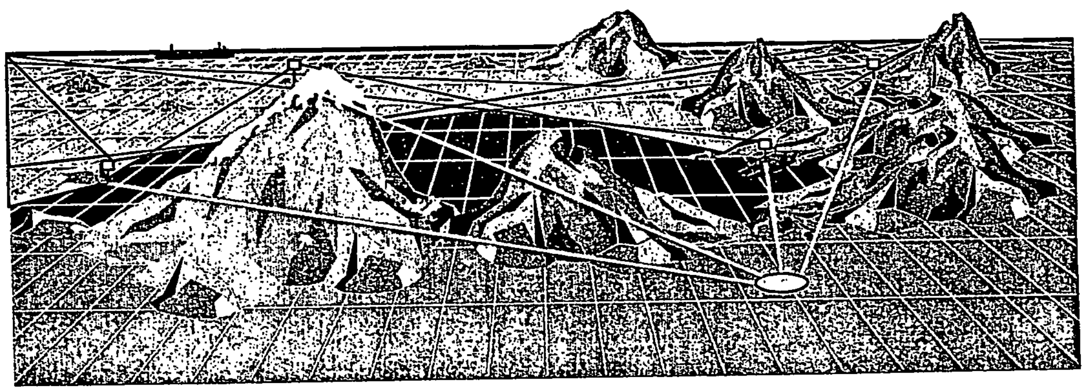


Figure 3-4: Multiple ESM-sensors networked for position determination, using a common emitter database for recognition

Emitter database maintenance is envisioned integrated with the ESM system. Whenever a new emitter is encountered, the emitter must be identified by other means, but the data is stored for recognition purposes.

The Processing Unit controls the Antenna, Receiver and Navigation unit with respect to frequency coverage (by controlling the amplifiers as shown in section 3.1.3). During battery operation, a several non-continuous operation modes may be specified in order to expand battery life.

The processing unit is contained in a single unit with integrated batteries in man-portable mode or rack mounted in platform installation.

3.1.3 Radio design

The radio design is based on a receiver in which the entire bandwidth is divided into multiple sub-bands. The resulting sub-bands are converted to a common intermediate frequency channel and then combined into a single channel. Signal from each sub-band are thus overlaid each other. Since the signals are pulsed, the probability simultaneous signal from different channels is quite low. In order to determine the frequency of each pulse, detection must be performed in each sub-band.

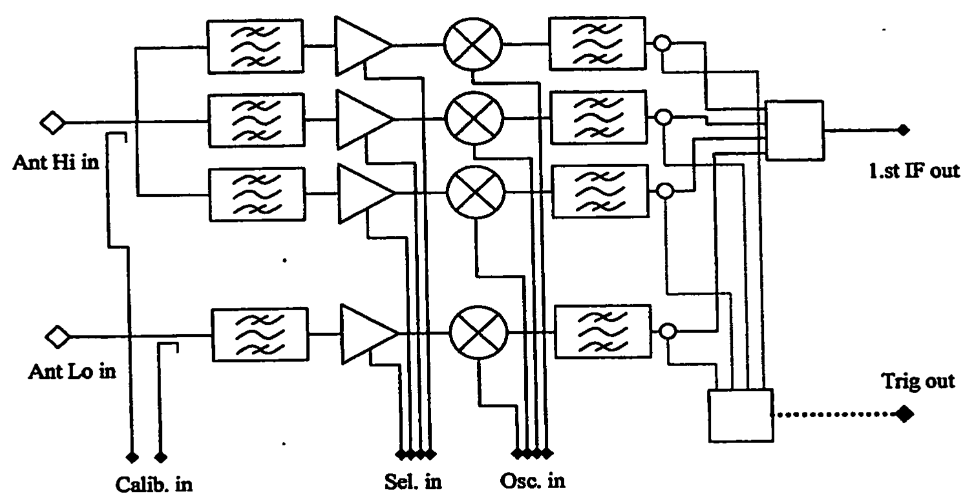


Figure 3-5: Receiver Front End

One such receiver is needed for each antenna direction. The IF-channels of opposing antennas are combined. Thus, with 6 antenna directions, the number of IF-channels becomes 3. Finally, the IF channels are divided into sub-bands with a bandwidth matched to the A/D converters (typ 1GHz with 2.5 GS/s A/D converters).

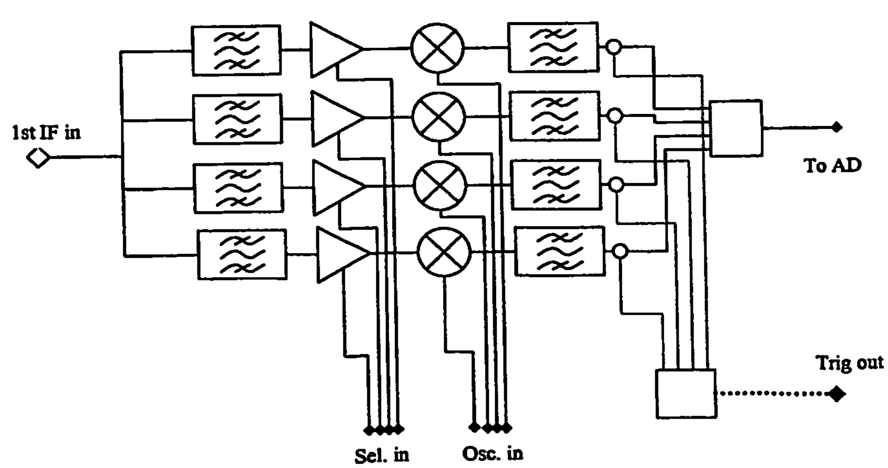


Figure 3-6: Receiver second stage

The resulting channels are narrow enough for A/D conversion, and the pulses may be processed with one single processor. The necessary number of parallel A/D converters is equal to half the number of antenna directions (typ 3 with 6 antenna directions).

3.1.4 Pulse processing algorithm

The processing system receives pulse signal from the radio head. The pulses are digitized in the sampler system such that each pulse is stored as 3 series of samples for each pulse, one series for each channel. In order to determine the pulse parameters, each pulse data series is analyzed with the following algorithm:

- Perform real to complex FFT (Fast Fourier Transform) for all 3 series
- Determine carrier frequency:
- Locate peak power in the series ($n_{\max}$), see Figure 3-7.
- Calculate carrier frequency: $f_c \approx \frac{n_{\max}}{N} f_s + f_{chan}$ where N is number of samples in series f_s is sampling frequency and f and f_{chan} is the frequency offset of the radio channel (received from the radio head)

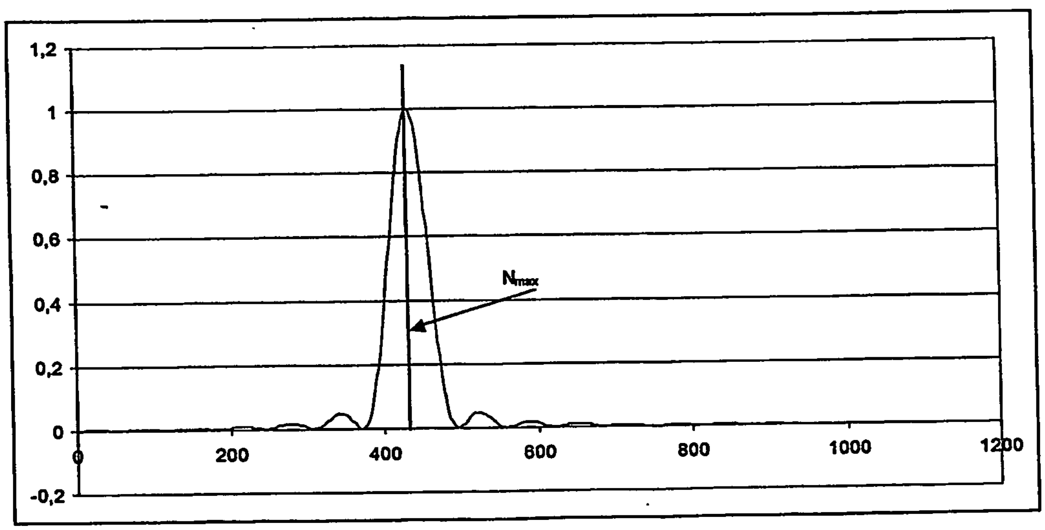


Figure 3-7: Calculating carrier frequency inf frequency plane

- Perform complex inverse FFT (The samples are now complex, and the series length is halved)
- Scan series and determine peak power ($P_{\max}$) for each channel and compute –3dB level: $P_{3dB} = P_{\max} / 2$
- Scan series and locate –3dB crossings, calculate 3dB pulse width (see Figure 3-8)
- Calculate time of arrival as data series start time + offset to first 3dB crossing

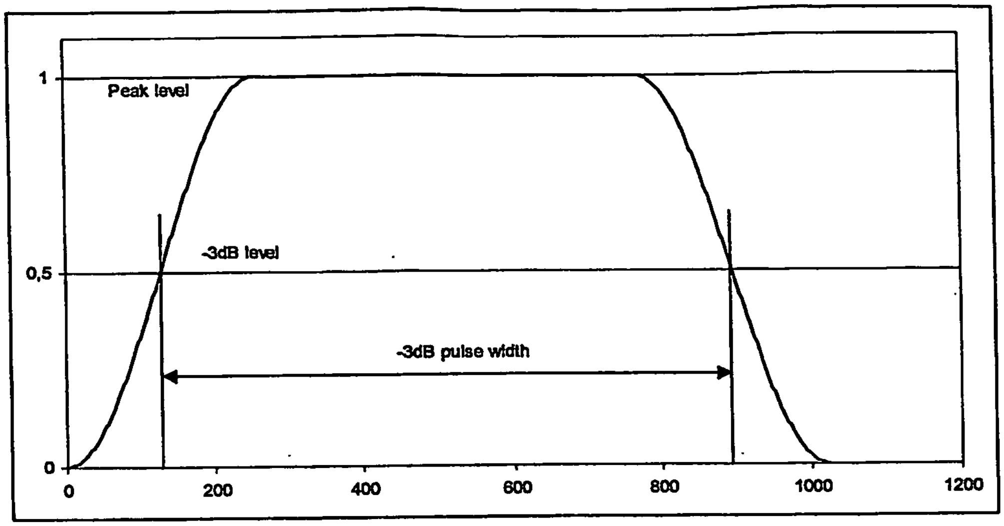


Figure 3-8: Calculating pulse width

- Estimate direction of arrival from pulse series from peak amplitudes:
  - Center channel (Ch_0) has maximum power (from radio head)
  - Calculate DOA from predetermined antenna lobe calibration function: $DOA = g(P_{-1}, P_0, P_1)$ see Figure 3-9.

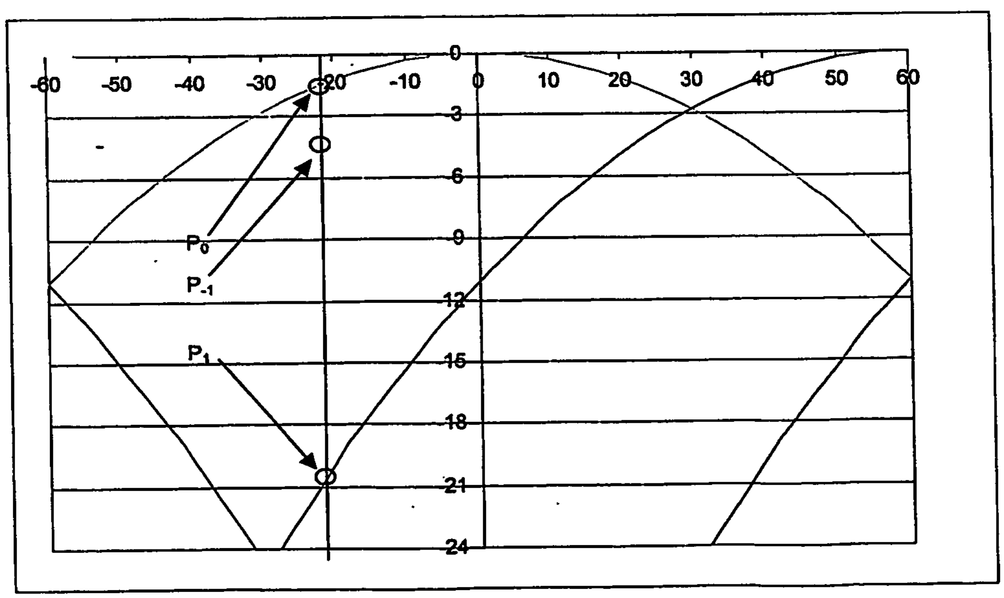


Figure 3-9: Calculating Direction of Arrival based on pre-calculated antenna lobe calibration function

- Insert pulse with parameters into 2-dimensional histogram, indexed by carrier frequency and direction of arrival

3.1.5 Emitter Processing algorithm

After detection and processing of a predetermined number of pulses (or upon reaching a predetermined time limit), a number of pulses from the observed emitters have been analysed and entered into the histogram. An example with two emitters i shown in Figure 3-10.

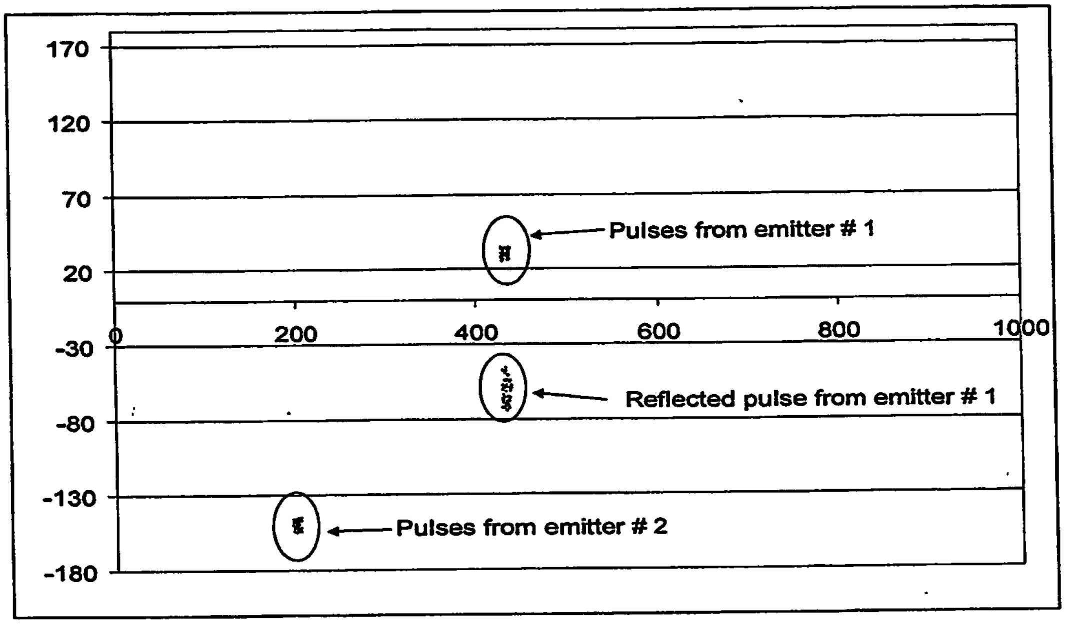


Figure 3-10: Pulses plotted in DOA / frequency

In order to de-interleave pulses (sort pulses by emitter), pulses are extracted from the DOA/frequency histogram, starting with the histogram cell with largest pulse count. In the above axample, 3 "emitters" would be extracted, namely pulses from emitter #1, pulses from emitter #3 and fimally pulses from emitter #1 reflected off a reflector (hillside, building etc). Each "emitter" is analyzed according to:

- Calculate average and standard deviation of all pulse parameters except pulse amplitude
- Perform Emitter antenna analysis (see Figure 3-11):
  - o Measure time between antenna main lobe passings (time from local maximum to local maximum)
  - o Measure antenna beam width (same principle as measuring pulse width)
- Perform emitter PRI analysis
  - o Measure time from pulse to pulse and calculate average

- Optionally: perform analysis of PRI variation (pattern recognition)

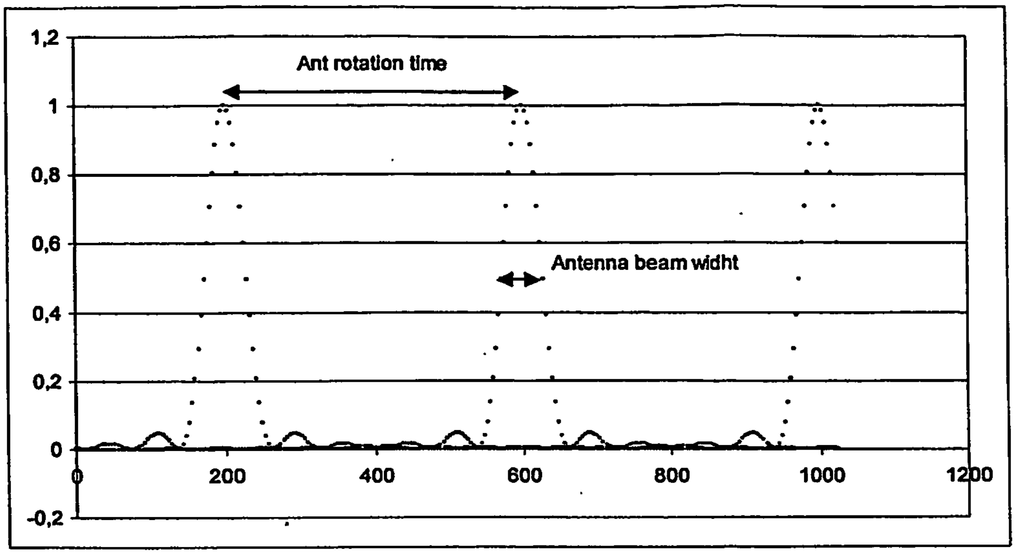


Figure 3-11: Measuring emitter antenna beam width and rotation time

After emitter parameter estimation, the directions to and other parameters to all emitters are known. The list also includes "emitters" that are actually copies of other emitters due to reflections off diferent surfaces. These artifacts have the same parameters as the originating emitter except Direction of arrival. In order to determine which emitter is the original the following analysis is performed:

- Compare peak amplitude. The artifact will most often have lower amplitude than the correct emitter

- Compare standard deviations of pulse parameters. The artifact will have larger standard deviations

The emitters are now analyzed and the direction of arrival, pulse parameters and emitter characteristics have been determined.

3.1.6 Emitter position determination usin multiple POS sensors

Each sensor analyze pulses from the observed emitters. When emitter analysis is complete, the emitter parameters are sent to any neighbouring POS sensors by data-network.

Upon reception of emitter parameters from a neighbouring POS sensor, this emitter is compared to all of the locally detected emitters (using all parameters except DOA). When a match is found, the position is determined by triangulation (position of each POS sensor is known, DOA to the emitter from each POS sensor has been determined, thus the emitter position may be determined by simple geometry)

3.1.7 Emitter recognition / Emitter database

In order to recognize emitters from previous observations, the emitter parameters are stored in a emitter database. Upon reception of a new emitter, the emitter parameters are compared with the parameters stored in the database. If a match is found, the emitter is assumed to be the same as the one found in the database. If not, the new emitter is stored in the database.

The database may either be stored locally or accessed by data network. Using a networked database provides the ability to share information about new emitters between multiple POS sensor as soon as the new emitter is detected.

3.2 Advantages

The full bandwidth is observed continuously, thus providing high probability of intercept. Each pulse may be analysed in detail, since the waveform is preserved. The system may be built with low parallelism in the digital processing (one single processor), thus providing the possibility to implement man-portable operation. At the same time, the system is capable of advanced emitter analysis and emitter recognition.

3.3 Broadening

The same principle may be used when measuring any signal where there is only one signal at a time and the frequency of the signal is unknown within a wide bandwidth.

3.4 Technical Abbreviations

A/D – Analog/Digital

DOA – Direction of Arrival

ESM – Electronic Support Messenger

GPS – Global Positioning System

GS/s – GigaSamples per second

IF – Intermediate Frequency

PRI – Pulse Repetition Interval

TOA – Time of Arrival

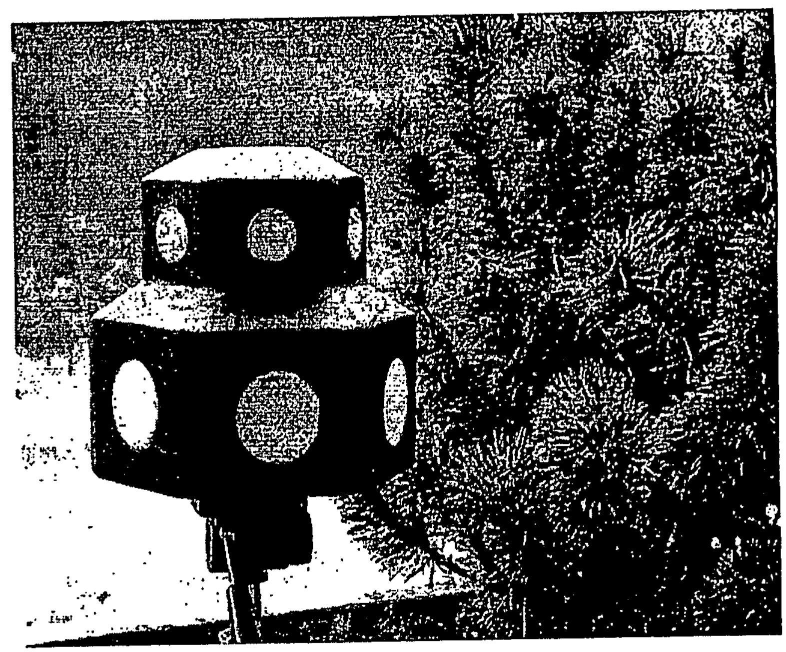
Lett ESM-sensor

- Egenskaper:
  - Allværskapasitet
  - Gir klassifiseringsinformasjon om mål
  - Retninginformasjon fra en sensor, posisjon fra flere sensorer

- Krav:
  - Lett / kompakt / kosteffektiv
  - Autonom
  - Frekvensområde 1: 2-18 GHz (radar)
  - Frekvensområde 2 : 0.02-2 GHz (kommunikasjon)
  - Vinkeloppløsning: ca 1°
  - Rekkevidde: 30 - 100 km (terreng- / horisontbegrenset)
  - Kapasitet noen hundre samtidig emittere
  - **Identifisering (gjenkjenning) av emitter (type, individ)**

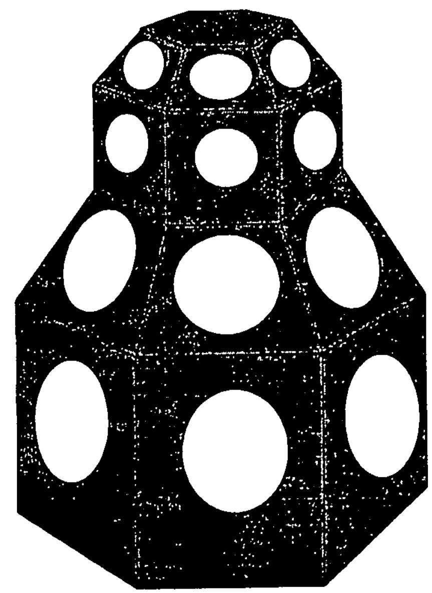
Prototype-karakteristikker (2D-versjon)

- Dekningsområde:
  - 360° azimut;
  - 60° elevasjon
- Frekvensområde:
  - 2-18 GHz, radar
  - 0.02-2 GHz Opsjon
- Antall mottakere:
  - 6 (120° pr antenne)
- Retningsnøyaktighet:
  - ca 1° azimuth
- Navigasjon:
  - Integrert GPS og kompass

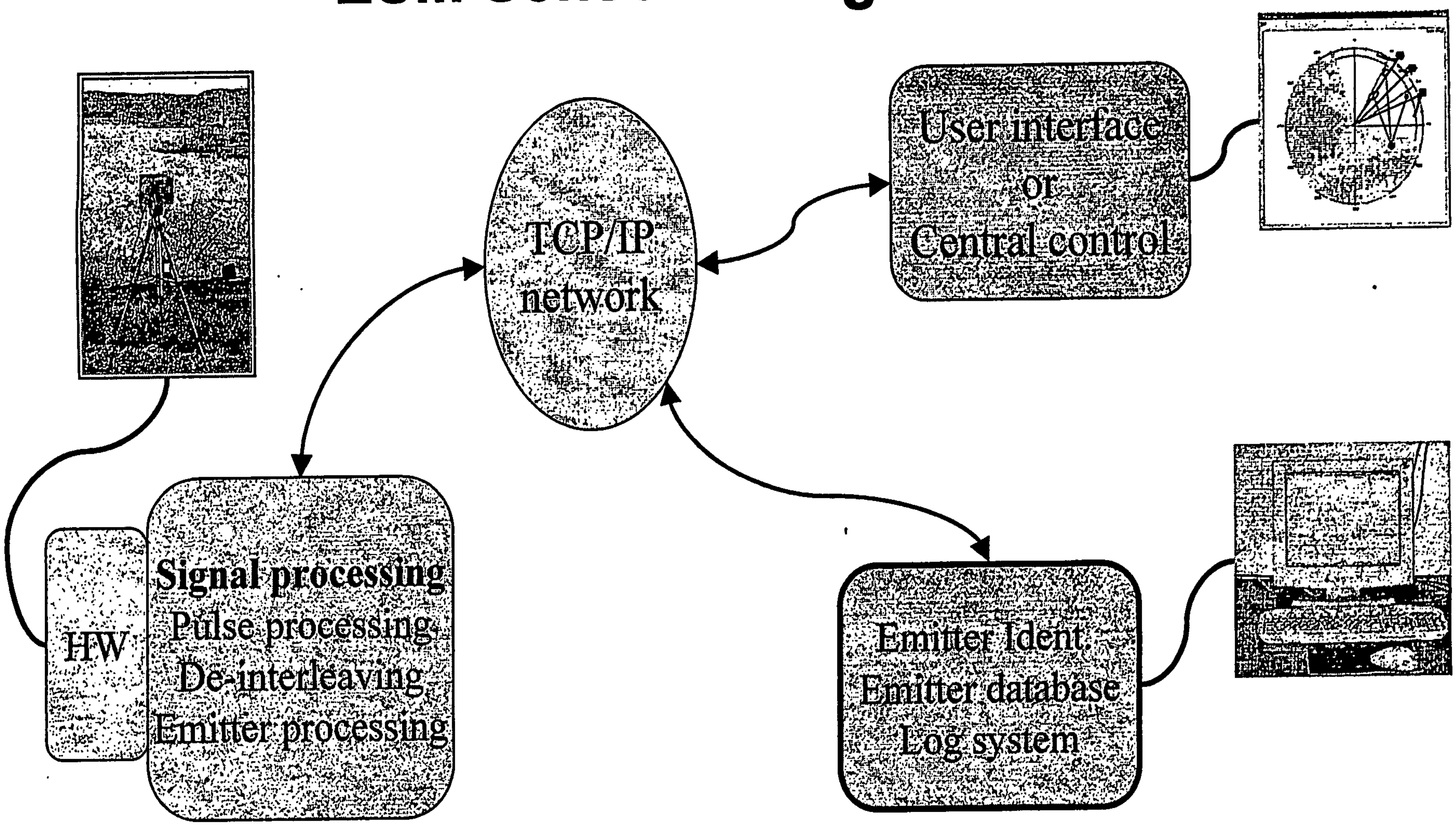


Prototype-karakteristikker (3D versjon)

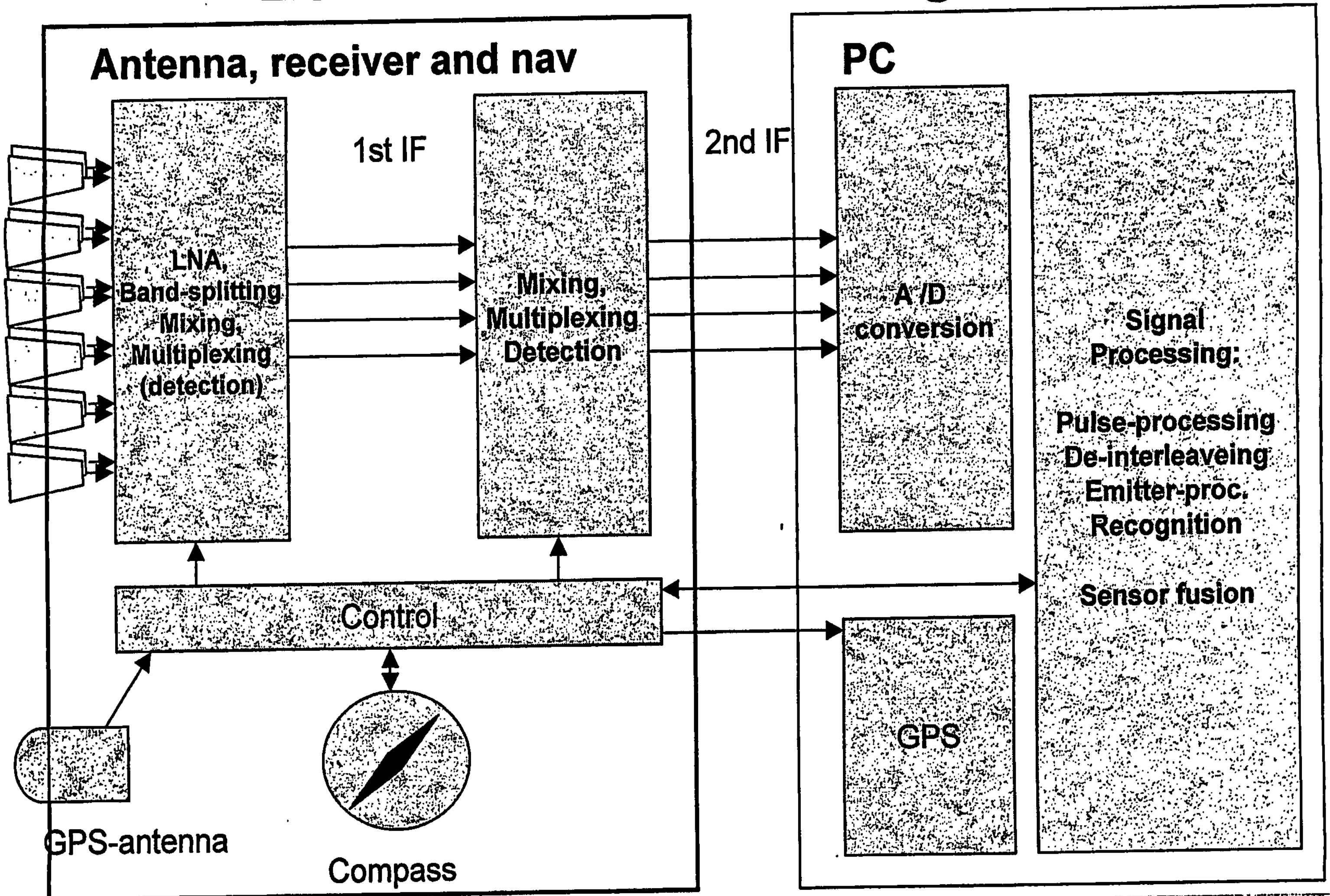
- Dekningsområde:
  - 360° azimut;
  - 60° elevasjon
- Frekvensområde:
  - 2-18 GHz, radar
  - 0.02-2 GHz Opsjon
- Antall mottakere:
  - 12 (120° pr antenne)
- Retningsnøyaktighet:
  - ca 1° Azimuth; ca 1° Elevasjon
- Navigasjon:
  - Integrert GPS og kompass



ESM Sensor - Programvare



ESM Sensor - Blokkdiagram



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OUTLINE SPECIFICATIONS

PROTOTYPE

LIGHTWEIGHT ESM SENSOR

1 Operational modes

The ESM sensor is a lightweight, compact unit that can be installed on various platforms including the use as a man-portable unit. The general concept is based on low cost, low weigth and low power consumption in order to accomodate a variety of uses:

ESM sensor for autonomous operations: The ESM sensor is operated as a stand-alone unit, either installed on a platform or used by the personnel. The sensor may be used for detection and recognition of radar sensors without revealing own position. During darkness and in low-visibility conditions (fog, rain and snow) an ESM sensor is probably the only passive sensor option.

ESM sensor for network operations: The ESM sensor is operated as part of a larger sensor network containing other ESM sensors and other classes of sensors. Multiple ESM sensors may detect, recognize and determine position of non-coalition active sensors. The ESM sensors are passive and can be – positioned close to interesting surveillance places. The ESM sensors can contribute with crucial additional information (recognition and classification) and in some cases provide sensor coverage where active sensors will provide limited or no information (e.g. ground surveillance of non-moving targets).

The ESM sensor design takes account of – the two basic operation modes. The sensor has built in functionality for autonomous operations with target tracking, local emitter database and a local user interface. In addition the sensor has network capabilities with built-in functionality for network operations with sensor fusion using two or more equal ESM sensors, ability to utilize distributed emitter database and ability to transmit sensor information over network for sensor fusion with other sensors.

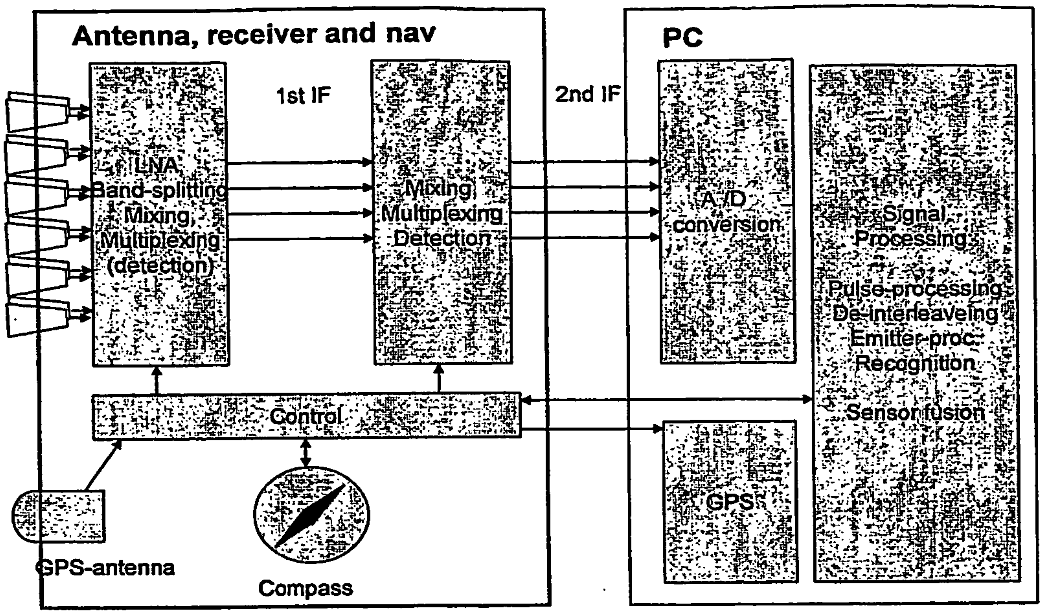
2 Applications

Coastal surveillance and vessel traffic control: The ESM sensor is capable of detection and classification of active radars at long range, limited by horizon. In addition, recognition is possible, thus providing additional information to active radar detection. The use of ESM sensors can complement AIS system when vessels do not respond to AIS and in areas where AIS is not operational.

Resource management: Surveillance of fishery may be complemented with ESM for recognition purposes. In addition, the ESM sensor has the ability to determine the number of active radars within a small area, thus improving long range resolution as compared to active radar.

3 Technology

The ESM receiver system consists of two units, namely the Antenna, Receiver and Navigation Unit and the Processing Unit. As shown in the figure below.



- <u>Antenna, receiver and navigation unit:</u> 12 antenna elements are used to cover 2 to 18 Ghz in 6 directions. The first stage in the receiver split the total band into four bands with an IF bandwidth of 4 GHz. The four bands are multiplexed into a single IF channel for each of the antenna sets (based on masks set from the processing unit). IF channels of opposing antennas are multiplexed into one channel, thus providing a total of three 1st IF channels.

  In order to determine direction and frequency of incoming pulses, broadband pulse detection is performed in each of the original channels before multiplexing.

  The second stage multiplexes the 4 GHz IF into narrowband 2nd IF channels of 500 MHz which are sent to the processing unit for digitalization and processing

  In addition to the antenna/receiver chain, this unit contain an attitude determination unit (compass) and a GPS antenna. All is contained within a single unit that may be mounted either on a tripod or fixed on an antenna mast.

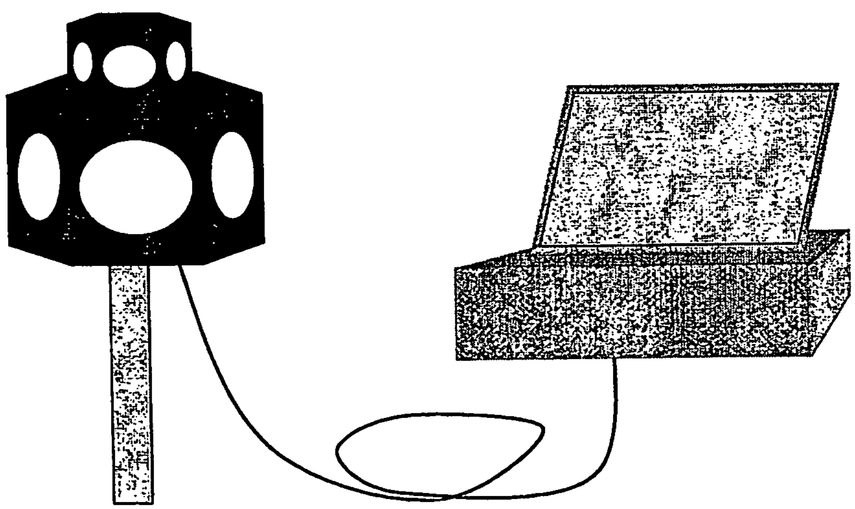
- Processing Unit: A four-channel 1GS A/D converter is used for digitalisation of the receiver channels. A GPS receiver is used for position determination, and the compass in the Antenna unit is read for antenna attitude determination. The processing unit digitises pulses received, performs pulse-processing, de-interleaving and multi-path analysis before emitter processing is performed. At this stage, data may be displayed locally or set to the network for sensor fusion with other sensors. If multiple ESM sensors are connected in a network, local sensor fusion may be performed to provide target positioning. In addition emitter recognition analysis is performed using either a local or network based emitter database.

  Emitter database maintenance is envisioned integrated with the ESM system. Whenever a new emitter is encountered, the emitter must be identified by other means, but the data is stored for recognition purposes.

  The Processing Unit controls the Antenna, Receiver and Navigation unit with respect to frequency coverage (by controlling the multiplexers). During battery operation, a several non-continuous operation modes may be specified in order to expand battery life.

  The processing unit is contained in a single unit with integrated batteries in man-portable mode or rack mounted in platform installation.

An impression of the physical design is given in the figure below:



The Antenna, Receiver and Navigation unit is designed as one compact unit (approximately 200 mm diameter) with the twelve antennas pointing in six directions for angle of arrival measurement. This unit may be mounted on a tripod when the system is used as a portable unit or fixed in an antenna mast. The unit is self-aligning by means of the attitude determination unit.

The processing unit will most probably be designed with a standard rugged compact PCI cabinet and contains processing, A/D conversion and a GPS receiver. Display unit and keypads will most probably be integrated with this unit.

This technical solution provides a compact, low cost system that may be operated with relatively low power consumption. The system design is relatively simple and the digital parts are based on commercial technology. The main draw-back of the system is the relatively low parallelism in the receiver system. All frequencies are mixed into a narrow 500 MHz channel, thus increasing the probability of simultaneous pulses in a dense environment. The Processing Unit controls may reduce this probability by excluding frequency bands successively or en the worst case scanning of the entire band one 500 MHz channel at a time. In the latter case, the scan time would be approximately 6 minutes in order perform full antenna scan analysis within each channel.

The pulse density in which the system may process continuously is determined mainly by the processing capabilities of the processing unit. Currently the processing capacity is approximately 20 kp/s with a single Athlon 1200.

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Initial Cost Asessment

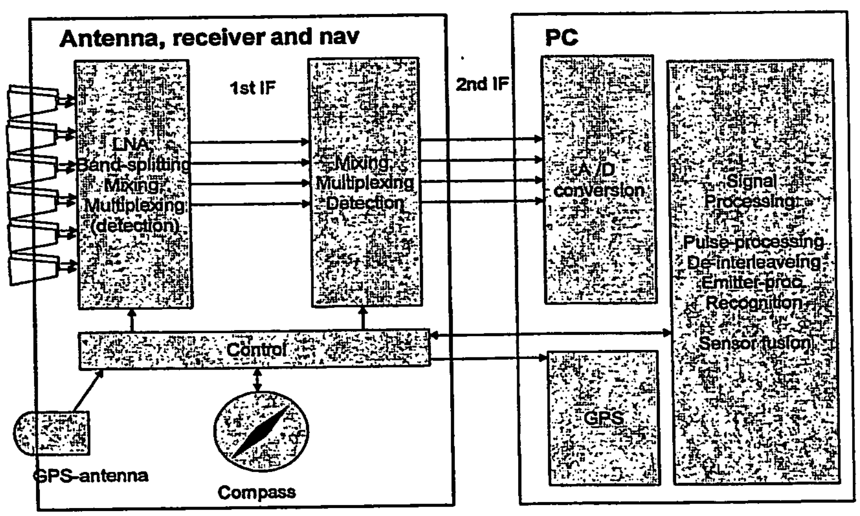
PROTOTYPE

LIGHTWEIGHT ESM SENSOR

1 Overall designOperational modes

1.1 System overview

The ESM receiver system consists of two units, namely the Antenna, Receiver and Navigation Unit and the Processing Unit. As shown in the figure below.



- Antenna, receiver and navigation unit: 12 antenna elements are used to cover 2 to 18 Ghz in 6 directions. The first stage in the receiver split the total band into four bands with an IF bandwidth of 4 GHz. The four bands are multiplexed into a single IF channel for each of the antenna sets (based on masks set from the processing unit). IF channels of opposing antennas are multiplexed into one channel, thus providing a total of three 1st IF channels.

  In order to determine direction and frequency of incoming pulses, broadband pulse detection is performed in each of the original channels before multiplexing.

  The second stage multiplexes the 4 GHz IF into narrowband 2nd IF channels of 500 MHz which are sent to the processing unit for digitalization and processing

  In addition to the antenna/receiver chain, this unit contain an attitude determination unit (compass) and a GPS antenna. All is contained within a single unit that may be mounted either on a tripod or fixed on an antenna mast.

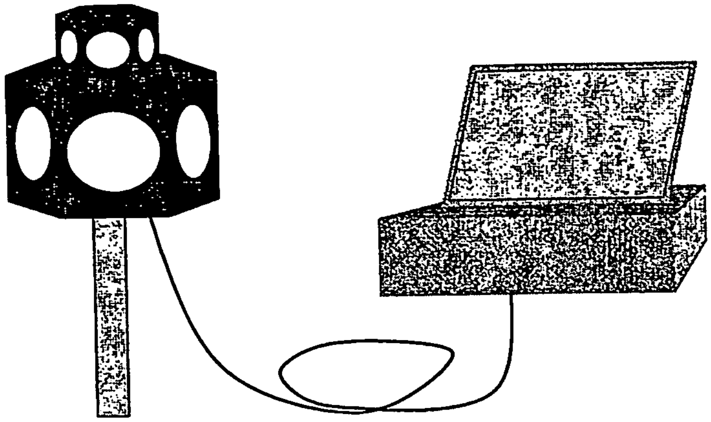
- Processing Unit: A four-channel 1GS A/D converter is used for digitalisation of the receiver channels. A GPS receiver is used for position determination, and the compass in the Antenna unit is read for antenna attitude determination. The processing unit digitises pulses received, performs pulse-processing, de-interleaving and multi-path analysis before emitter processing is performed. At this stage, data may be displayed locally or set to the network for sensor fusion with other sensors. If multiple ESM sensors are connected in a network, local sensor fusion may be performed to provide target positioning. In addition emitter recognition analysis is performed using either a local or network based emitter database.

  Emitter database maintenance is envisioned integrated with the ESM system. Whenever a new emitter is encountered, the emitter must be identified by other means, but the data is stored for recognition purposes.

  The Processing Unit controls the Antenna, Receiver and Navigation unit with respect to frequency coverage (by controlling the multiplexers). During battery operation, a several non-continuous operation modes may be specified in order to expand battery life.

  The processing unit is contained in a single unit with integrated batteries in man-portable mode or rack mounted in platform installation.

An impression of the physical design is given in the figure below:



The Antenna, Receiver and Navigation unit is designed as one compact unit (approximately 200 mm diameter) with the twelve antennas pointing in six directions for angle of arrival measurement. This unit may be mounted on a tripod when the system is used as a portable unit or fixed in an antenna mast. The unit is self-aligning by means of the attitude determination unit.

The processing unit will most probably be designed with a standard rugged compact PCI cabinet and contains processing, A/D conversion and a GPS receiver. Display unit and keypads will most probably be integrated with this unit.

This technical solution provides a compact, low cost system that may be operated with relatively low power consumption. The system design is relatively simple and the digital parts are based on commercial technology. The main draw-back of the system is the relatively low parallelism in the receiver system. All frequencies are mixed into a narrow 500 MHz channel, thus increasing the probability of simultaneous pulses in a dense environment. The Processing Unit controls may reduce this probability by excluding frequency bands successively or en the worst case scanning of the entire band one 500 MHz channel at a time. In the latter case, the scan time would be approximately 6 minutes in order perform full antenna scan analysis within each channel.

1.2 Radio Head

The radio head consists of one integrated unit with 12 antennas pointing in 6 different directions and a receiver system as shown in the overview. Th receiver system block diagram is shown below.

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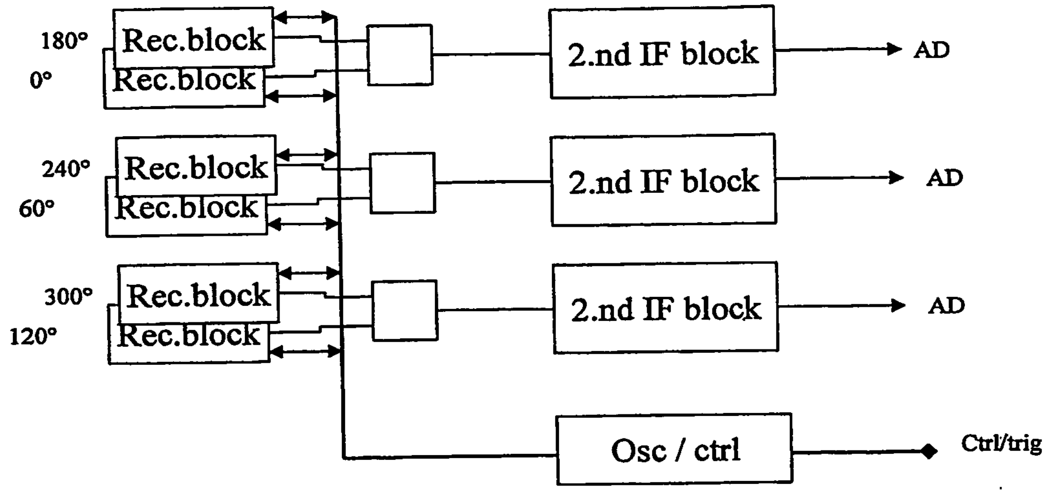
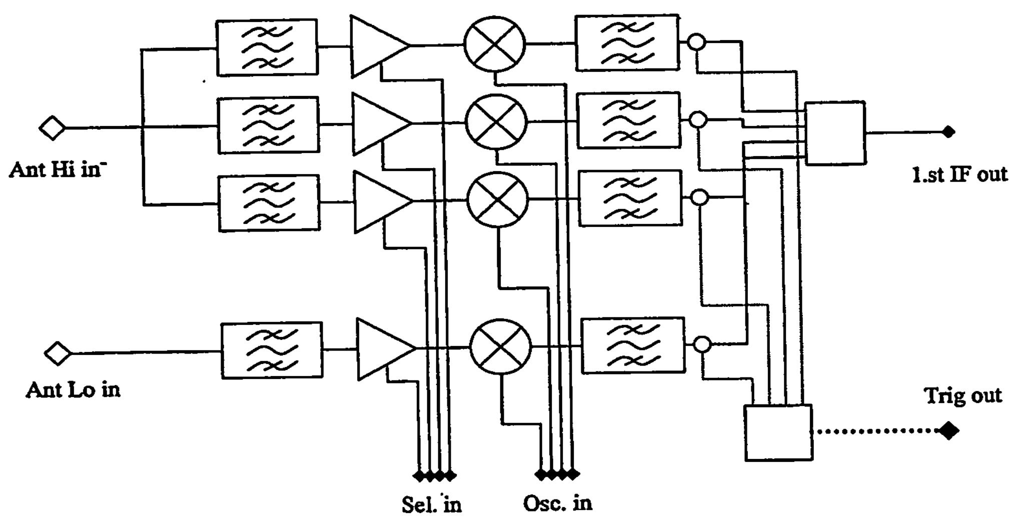


Figur 1-1: System Block Diagram

The design is based on two main blocks, namely the "Single direction receiver block" and the "2nd IF block". The block diagram of the "Single direction receiver block" is shown below.



Figur 1-2: Single direction receiver block diagram

The block diagram of the "2nd IF block" is shown below.

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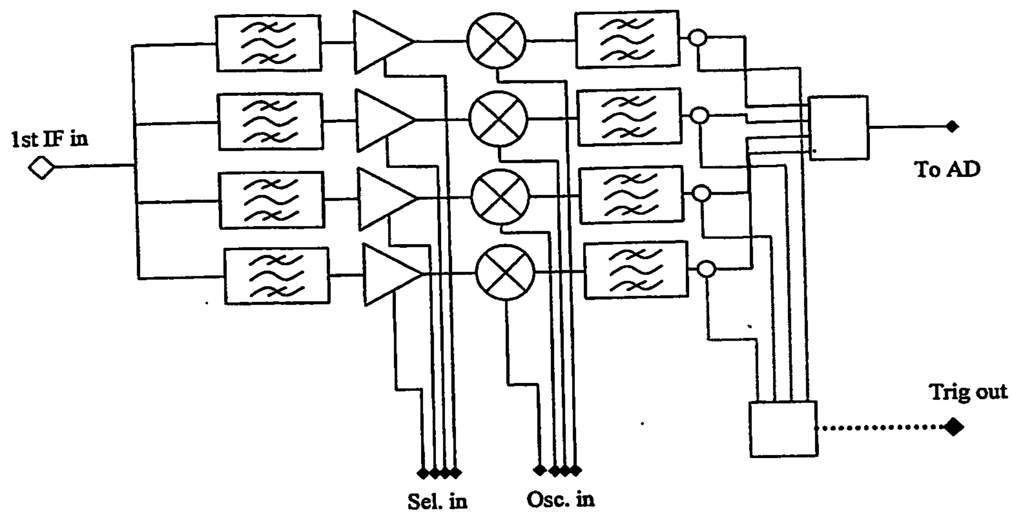

Figur 1-3: 2nd IF block diagram

In addition a Oscillator and control block is needed to generate all oscillator frequencies, control signal to the amplifiers and handle trigger signal from each of the channels.

2 Cost estimate

Two different design methodologies may be applied for a prototyping of the receiver system:

- LTCC design: has high initial costs but low production costs. Such a design could continue into a production model
- SMA module design: has very low initial costs but very high production costs. This design is not applicable to a production model due to high component and manufacturing costs.